Zieth, P. J., Gravina da Rocha, C. (2024). Defining Interfaces to Facilitate Building Module Change. In D. B. Costa, F. Drevland & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction* (IGLC32) (pp. 845–856). doi.org/10.24928/2024/0137

DEFINING INTERFACES TO FACILITATE BUILDING MODULE CHANGE

Peter Zieth[1] and Cecilia Gravina da Rocha[2]

ABSTRACT

Modular construction in the building industry remains largely misunderstood, despite numerous studies on the subject. With confusion around what constitutes a module, how it is defined and differentiated from other modules, and how they interface. This study examines interface characteristics; types, standardization, and reversibility (three measurable categories based on Fixson (2005) function-component allocation (FCA) tool for product architecture assessments) and assesses product architecture interfaces to apply them to building product architecture. The intent of this examination is to understand the interface's role in any transfer of module functions across modules. Defining interfaces to better differentiate building modules from each other should ultimately facilitate the identification of what specific functions of the building component modules that need to be designed, manufactured, assembled, changed, and disassembled. From the examination, the discussion arising seeks to advance on how a building spatial module function designation might transfer functions at an interface, to provide clarity on the functional requirements for component modules to meet.

KEYWORDS

Modular construction, prefabrication, flexible manufacturing, interfaces.

INTRODUCTION

Modular construction in the building industry remains largely misunderstood, despite numerous studies on the subject. With confusion around what constitutes a module, how it is defined and differentiated from other modules, and how they interface. In the context of product architecture (or product modularity) each component, or module, can be made up of modular sub-components, or connected subassemblies. Likewise, each module, when connected, forms a product (Ulrich, 1994). Further explained in the referenced authors' study, these connections, or interfaces, can be coupled, such that a change to one component requires a change to the other (e.g., changing a ball hitch size on a car requires a change to the hitch on the trailer which is to be attached) or de-coupled (Figure 1) where no such dependency exists (e.g., a mobile phone and protection case). While a modular architecture includes one to one mapping of the function to the component (e.g., for a car trailer, the function being the transfer of a load to the road is mapped to the wheel component), an integral architecture includes complex mapping of functions to components (e.g., a car chassis) (Ulrich, 1994).

As has been studied, those interfaces may be 1) coupled (nuts and bolts), tightly coupled (welded joints), decoupled (furniture in a room), or loosely coupled (door hardware and door

---

[1] PhD Student, School of Civil Engineering and Environmental Engineering, University of Technology Sydney (UTS), City Campus, Broadway, Bldg 11, Lv 11, NSW 2007, Australia, peter.zieth@student.uts.edu.au, orcid.org/0009-0008-9546-2895

[2] Senior Lecturer, School of Civil Engineering and Environmental Engineering, University of Technology Sydney (UTS), City Campus, Broadway, Bldg 11, Lv 11, NSW 2007, Australia, cecilia.rocha@uts.edu.au, orcid.org/0000-0002-2649-2432

leaf) (Sanchez, 1995; Schilling, 2000; Ulrich, 1994), or 2) an interface type across families of modules (doors to walls across room types) (Pine, 1999; Salvador et al., 2002). Both sets of interface types have applicability in building modularity.

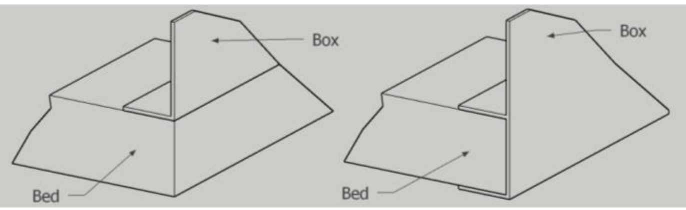

Figure 1: De-coupled Interface, left, Coupled Interface, right.
(Adapted from Figure 4 in Ulrich, 1994)

Using Ulrich's definition of a module, a study (Fixson, 2005) looked at (i) what is a function, (ii) what is a component, and (iii) how the function was allocated to a component. While the first part of the Fixson study is important in framing a discussion on modules, how a function is allocated to a component (modular or not) could apply to a product and a building product equally and is therefore not the focus of this study. Understanding interface characteristics though and their role in the functional allocation transfer from one component to another potentially has the greatest ability to facilitate building module decoupling and change.

Ulrich proposed six motives for change in products (upgrades, add-ons, adaption, flexibility, wear, and consumption) (Ulrich, 1995). Changing, making, and unmaking a building product is of particular interest since buildings are typically designed and constructed to serve a specific function for an expected period (Askar et al., 2021), namely, its design (or service) life. When applying Ulrich's motives for change to the design life of building product components, they could be organized into three groups: (i) replacement (wear and consumption), (ii) retrofit (add-ons and adaption) and (iii) change in use (flexibility and upgrades).

Regardless of the mechanism initiating change, design strategies (specific plans of action to accomplish an objective or set of objectives) which increase the flexibility of a building, and allow for change to be easily carried out, have been studied (Gosling et al., 2013; Keymer, 2000; Slaughter, 2001). These include strategies grouped into; the use of interchangeable system components, increased layout predictability, improved physical access, dedicated areas for systems, among others, but do not examine a process designers can use to facilitate these strategies. Other authors have looked at the absence of initial design consideration for potential change that leads to different levels of disruption in building operations once component parts of a building need to be changed (Gleeson et al., 2011; Grussing & Liu, 2014; Knyziak et al., 2017). Indeed, occupants can be subjected to a diminished use of the building in normal day to day activities once changes need to be performed (Tokede & Ahiaga-Dagbui, 2016). One of the studies (Gleeson et al., 2011) categorized disruption and demonstrated that different levels of disruption are connected to the complexity/extent of change (intervention), and highlighted the importance of identifying change potential to guide the design of components and the relationship to adjacent components. What the components do, what their interfaces are, and their arrangement with the rest of the product is referred to as the product architecture (Eppinger & Ulrich, 1995; Fixson, 2005; Gershenson et al., 2003; Ulrich, 1995; Vickery et al., 2015). What these studies don't do, and is needed, is to provide a consolidated process for designers to use that lead to design outcomes that can facilitate change activities while limiting disruption.

The second part of the Fixson study examined product interface characteristics, types, the degree of interface standardization, and the interfaces' role in making, changing, and unmaking (disassembling) the product (its reversibility). When considering a building as a product, it becomes important to understand the definition of an interface between modules to better identify the type of coupling, what is the level of modularity (modular or not), and what the modules are. The aim being to evaluate an alternative interface definition to help identify and distinguish building modules more clearly so they can be manufactured and assembled, while also facilitating change, the speed of construction, disassembly, maintenance activities, and environmental outcomes for material reuse and recycling.

Conducting desktop research of literature identified an issue with applying a definition for interfaces from product modules to building modules. The literature review looked at the basic differences between building product architecture as compared to product architecture before examining how building module interfaces are identified between building modules. This review conceptually examined how interfaces might be used to facilitate change. The study then considered parameters that define an interface, before devising and applying an alternative conceptual interface definition to the Fixson study, specifically when conceptually applied to buildings. Particular attention is given to the interface characteristics of type, reversibility, and standardization before a conclusion is drawn and implications are identified. The developed knowledge from the research and analysis will help to better identify and differentiate one building module from another and can be further tested using more analytical research methods.

BUILDING PRODUCT ARCHITECTURE

When applying the concepts of product modularity to buildings, there is a key difference between buildings and products. Buildings utilize components to create spaces typically occupiable by people, whereas products typically involve only the physical components (C. Rocha et al., 2015). An obvious exception may be cars, that contain spaces occupied by people, but differently, buildings are anchored/founded on a specific piece of land. Buildings also typically have longer life cycles and involve multiple different stakeholders influencing their change over that period (Menassa & Baer, 2014), and they often remain occupied while changes occur to them. Whereas modular (or integral) products, like a car, tend to be deactivated completely while change occurs (e.g., changing a wheel, or a battery). It also implies that if a building typically remains occupied while changes occur to it over time, there is a potential high degree of change variability inherent due to the diversity of potential stakeholder input. Whatever those changes are should also facilitate the ability for occupants to remain while the changes happen to the affected components, and those components should be made to be easily changeable to limit the disruption to occupants.

BUILDING MODULE INTERFACES

To facilitate the potential for change to modules in buildings, there must be an initial recognition of the differences between product and building modularity. Examining the concept of product modularity levels (a chunk, divided into sub-chunks), and how they could be divided, as applied to buildings, was a study (C. G. da Rocha et al., 2018) that focused on modules being spatial voids (rooms) with components being used, or not used, to create spaces (with walls and doors, for example, being used to differentiate one module family from another, Figure 2). There are two outcomes of this study worth highlighting: (i) components are not needed on all sides to define a space, but the interface connection between spatial modules is, and (ii) spatial voids are formed by at least six surfaces (the latter logically assumes rooms are cuboid).

The Rocha and Koskela (2018) study conclude there are interface connection surface problems at the junction between two modules. In this case, the interface connection surface is a single shared wall of two different spatial modules like a Bedroom (Room B) and a Bathroom (Room A) on either side of the wall in Figure 2. With the interface connection problem being where the two modules have potentially different requirements for that shared wall, like the location of a door that necessitates changes to the components forming another module like the

Bathroom cabinet in A1 to B2 modules in Figure 2. It implies the interface may not be correctly identified or located between modules.

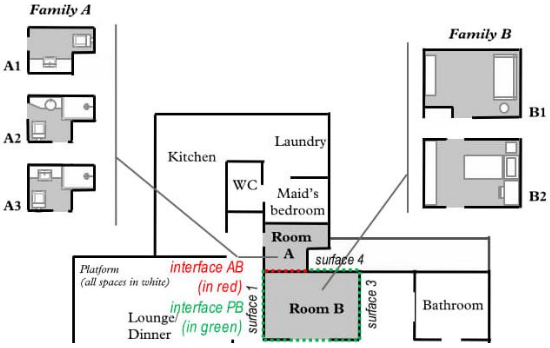

Figure 2: Example of building module component variances from the differing positions of fixtures, doors and windows, and services. (Adapted from Figure 2 Rocha and Koskela 2002)

The Rocha and Koskela (2018) study considered spatial modules to also contain building components such as walls surrounding a spatial void, along with other associated doors, windows, and fixtures. While component-oriented building modules are not always bounded by components on all sides, due to the arrangement of boundary components, a change to one module necessitates a change to an adjacent module. The result implies these modules are more integral and requires clarity of the interface definition if a modular outcome is desired.

Maintaining the assumption that spatial void modules are cuboid and formed by at least six ‘surfaces’ implies that modules are limited in their ability to be universally adaptable (sectional modularity) with other modules since the surfaces (including doors, windows, fixtures etc.) of a particular module are fixed. Hence that module is limited in its ability to be universally adaptable for use with other modules because of the location of those features that conflict with the adjacent module at that interface. Further a module interfacing with another module along the length of a shared wall, between Rooms A and B in Figure 2, points to potential difficulties of constructing, manufacturing, and coordinating individual modules to facilitate a connection.

However, the interface surface problems could be resolved if modules are more clearly differentiated by viewing and defining the interface differently. Firstly, a building product architecture could be a combination of both component-oriented and space-oriented modules. This is not a new concept, but it needs to be described to understand the second point. A building module could be a component (door, wall, window, floor) and it could be a spatial void (room) (Figure 3) to make the appropriate scale of these module interfaces invariant. While a component may be an object, like a wall, a spatial void could also be considered a component because a function can be mapped to it. For example, placing a bed in a room implies the function of a room is for sleeping and is therefore a Bedroom. Applying this perspective to building modularity means that every surface of a spatial void (room), and every surface of an object component (wall), all being different modules, could interface with each other.

Secondly, if the proposal was that spatial voids are formed by at least six ‘planes’ (e.g. boundaries without physical mass between two spatial voids) instead of ‘surfaces’ (e.g. associated with a solid mass such as a wall), then there is flexibility in the definition of a building module to allow for interfaces with other modules that are not dependent or linked to a surface. This approach places emphasis back onto the role and characteristics of the interface.

The notion that a module could interface via a ‘plane’ with either a component that has surfaces (i.e. physical mass), or another spatial void constituting any number of ‘planes’ (i.e. voids), provides a more appropriate product architecture module definition to a building. It allows, for example, walls, portions of walls, or the absence of a wall (the void that might otherwise be occupied by a wall defined by its ‘planes’), all to be modules, and rooms (or voids) to be modules, with or without walls.

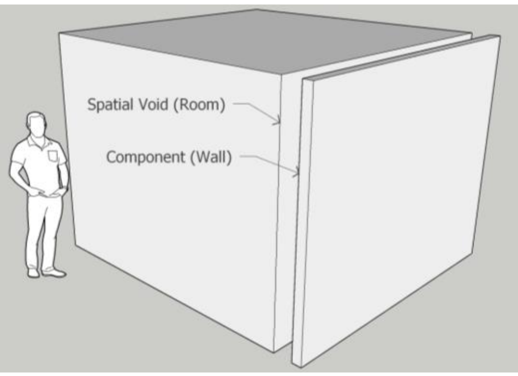

Figure 3: Component-oriented (wall) and Space-oriented (room) building modules where every surface of each module is an interface.

By extension, if consideration of the spatial void definition is applied to a component, then, a component, having surfaces that are co-located with a plane means that all building modules, be they spatial voids or components, are bounded by planes (having no physical mass). This means that all building modules have planes that interface with other planes. Simply, the building module plane is the interface, regardless of it having a surface or not.

BUILDING MODULE INTERFACE DEFINITION

The concept of product modularity initially focused building modularity on being spatial voids (rooms) with building components being used, or not used, to create the spaces. Further analysis of literature resulted in concluding that a product architecture module definition for a building could be that (i) a module (spatial or component) could interface with either a component, that has surfaces, or a spatial void constituting any number of planes, and (ii) while components are not needed to define a space, and a space could itself be a component, an interface connection between modules is required. This definition raises two questions 1) if a module could interface with either a component that has surfaces, or a spatial void that has planes, would it be simpler to refer to the component surfaces as planes, and 2) if components are not needed to define a space (ceiling or walls for example), is there a limit to the number of adjacent components required in order for that space to be considered a component module?

If a module's surface coincides with a plane, then the first question is addressed. However, if the second question was not addressed, it could be surmised that a cubic void of air not within a building could be considered a building module. While there are practical benefits to defining exterior air 'space' as a module when allocating functions from that space to a building module to address (wind, radiant heat from the sun, rain, atmospheric pressure, humidity, for example), this interpretation is useful only in allocating those atmospheric functions to the building and its constituent component parts. Namely, from an overall building module set of functional requirements allocated to the rooms and wall modules being examined here. Maintaining the limitation of applying building modularity to physical buildings, and not outdoor natural environments, it therefore implies that a building module must be bounded by components: a built environment having a floor at least. How people perceive a defined space is not the subject of this paper, however, the purpose of the distinction is to clarify a revised product architecture module definition for a building. That definition being that a building module (i) constitutes any number of planes that coincide with component surfaces and spatial void boundaries, and (ii) an interface connection between modules is required. A building module could therefore be either a spatial void that has met certain boundary conditions, or a component, and requires an interface connection. This conclusion is reinforced by a study (C. Rocha et al., 2015) that aimed to adapt product modularity to be used for house building that concluded solid mass components (walls, roof, floors) create spatial voids for the activities of the people within.

Returning to Ulrich's concept that a modular architecture includes one to one mapping of a function to the component, and an integral architecture includes complex mapping of functions to components (Ulrich, 1994), requires examination of the application of functions to building modules when considering the module interfaces. Using Ulrich's definition of a module, a study (Fixson, 2005) looked at (i) what is a function, (ii) what is a component, and (iii) how the function was allocated to a component. As referenced previously, while the Fixson study is important in framing a discussion on modules, it is the interface characteristics and role in the functional allocation transfer from one module to another that potentially has the greatest ability to facilitate change of building spatial or component modules. It is the examination of product interface characteristics, types, the degree of interface standardization, and the interfaces' role in making, changing, and unmaking (disassembling) the product (its reversibility), that is of interest, and applying them to a building product architecture to see if they can facilitate change.

The result of the Fixson study was the development of a tool (a device or implement to carry out a particular function) for assessing interface linkages between the product, process, and supply chain of different designs of similar products. This tool, albeit intended for manufactured products, could be adapted for application to assessing building modules and is the subject of what is tested in this study. The intent of adapting the tool would then be to reverse engineer it for possible use to define adjacent component modules more clearly for manufacturing purposes.

To assess how the tool could be adapted for application associated with building modularity, an understanding of the interface role needs to be examined against the product function for its nature and intensity as applied to a building using the definition of an interface being a plane. For the purposes of demonstrating the concept as applied to building modularity, I will use a building in the form of a six-sided cuboid that contains a series of cuboid forms (room spatial modules) linked together and separated by other, narrower cuboid forms (walls and floors component modules) like those of other studies (Ching, 2023; C. Rocha et al., 2015). Figure 4. For further simplification and clarity, the exterior boundary cuboid forms (exterior walls, floor, and roof component modules) will not be used in the demonstration and can be examined in further studies. Using two adjacent room component modules of similar function, for example, a bedroom-to-bedroom relationship, there are characteristics (privacy, insulation, visual amenity, for example) of the component function (bedroom 1) that must be transferred through the interface plane (interface characteristics) into the component function of another product (wall) for that product to perform (opacity for privacy, insulate for warmth, color and texture for visual amenity, for example) prior to transferring through another interface plane (interface characteristics) to another component function (bedroom 2) for it to perform (opacity for privacy, insulate for warmth, color and texture for visual amenity, for example) and vice versa. Figure 5.

The Fixson study (Fixson, 2005) assessed three different interface characteristics: (i) type (the interfaces role for the product function), (ii) reversibility (the interfaces role for making, changing, and unmaking the product), and (iii) standardization (the interfaces role regarding substitutes). These will be recapped below with interpretations of how they might be applied to a building product architecture.

TYPE

According to the Fixson study, the type of interface is initially determined by (i) their number and distribution across the product, (ii) their nature, and (iii) their intensity.

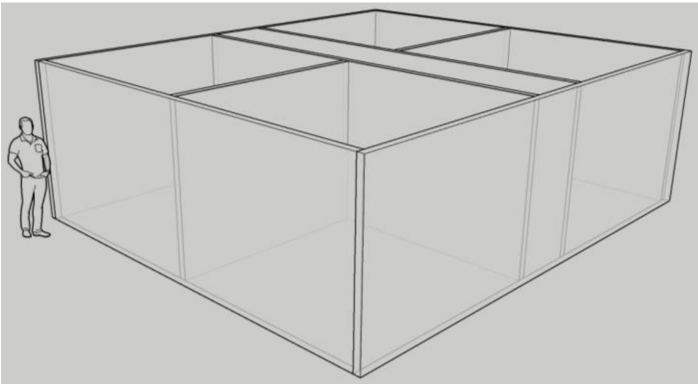

Figure 4: Cuboid that contains a series of cuboid forms (room component modules) linked together and separated by narrower cuboid forms (walls and floors component modules). Roof/Ceiling removed for visual simplicity.

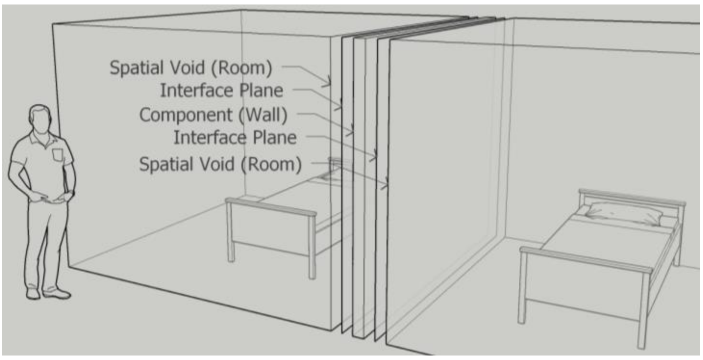

Figure 5: Bedroom-to-bedroom component function (bedroom 1) transfers through the interface plane into the component function (wall) to another interface plane to component function (bedroom 2) and vice versa.

Determining the number involves a simple counting of the interfaces. In the example, these interfaces are the boundary planes. A room component module shown in Figure 5 has primarily six; the ceiling, the floor and four walls. This number could be expanded if there was a window component module in one wall and a door component module in another, for a total of eight. Honing the example, for a wall separating the other room, there is only one interface plane to each adjacent component, the room to wall, or two interface planes if you add a door. Services (electrical, ventilation, communications systems, for example) interfaces are not referenced here for simplicity. They are sub-components for this example and an outcome of how the interfaces of the room to adjacent components are managed and functions are allocated.

Distribution examines if a component interface interacts with a limited or significant number of other components (relative to the total number of components) (Fixson, 2005). If the interface does interact with a significant number of other components, the component may be general or central to the functionality, indicating if the product architecture is not very modular but fragmented. Fixson postulates that a fragmented product architecture is more likely to have many components that show interactions with many other components. This also generally applies to a building since the room component modules generally interact with a variety of other adjacent modules (walls, floor, ceiling, doors, windows, other rooms, and services of varying types) through their interface planes and is consistent with Ulrich’s Integral product architecture. However, this is not the focus of this study.

It is the function of a room module that distinguishes it from another room module. At a very basic level, a Bedroom is called a Bedroom because it has a bed in it and is used for sleeping. A Dining Room has a table and chairs used for eating at. That is not to say that either of these examples cannot be used for other functions, but those other functions influence the functional allocation of that space, and hence the transfer of those functions to the interfaces for the adjacent components to meet, or not. Hence, the functional allocation has the potential to affect the adjacent component being manufactured.

Fixson's tool utilizes the outcomes of another study (Pimmler & Eppinger, 1994), that combines the nature of the interface (reflecting the physical effects that occur for the interface to play its intended role), and its intensity (its strength and desirability with respect to its nature), to assess the interface between components. At the component level, the tool assesses four types of interactions: (i) a spatial interaction (the need for adjacency or orientation – room to room adjacency for functionality, room to wall), (ii) an energy interaction (the need for energy transfer – room to wall for insulation, of heating), (iii) an information interaction (the need for information or signal exchange – room lighting activation), and (iv) a material interaction (the need for an exchange of materials – the passage of people through a door, or wind through a window opening). These interactions are further assessed by their importance and desirability levels. Each of these four interactions, at the interface, apply to building modularity and can be tested accordingly as was studied by da Rocha et al. (C. Rocha et al., 2015).

REVERSIBILITY

Considered to be an advantage of modular product architectures reversibility is the ability to change products over the product life, such as upgrades, add-ons, adaptation, wear, consumption, or reuse, and depends on the interface. The ability of a module to change depends on the difficulty to disconnect at the interface, and the interface's position in the overall product architecture (wall to floor being more inaccessible than a wall to room interface). In the example, the ability to change the room function, from Bedroom to Living Room, will be dependent on the ability of the interface planes reversibility with boundary components. Changing from one spatial module type to another requires changing function allocations at an adjacent wall component interface plane. If the wall component module meets the requirements of the interface, then reversibility conditions have been met. However, if the wall needs to be replaced due to it not meeting the performance requirement needed, then the ability to remove and replace the wall as facilitated by the wall components other interface planes (floor, ceiling, and adjacent wall component modules) is a measure of the components reversibility. For a wall it is not just one interface plane that is required to be reversible, but six. An example of low-level of reversibility of a component module might be a wood framed gypsum board wall that requires destructive removal of the gypsum board to expose stud framing nailed to the floor, that also needs destructive removal. Refer to the left side of Figure 6. A high-level reversibility might be a prefabricated wall finish panel clipped onto a wall frame that is bolted to a floor and ceiling. Undoing these clips and bolts facilitates removal and replacement without the levels of destruction the former example necessitates, as shown to the right side of Figure 6.

Fixson uses two measurables for reversibility; (i) the interfaces' own technical specifications (skill and equipment requirements to change the component), and (ii) how deep the component is 'buried' in the product. In the former, the room (spatial module) to wall (component module) relationship requires the interface plane to require the room function to be accommodated by the wall component function through the interface plane exchange and vice versa. What those requirements are will be the subject of further study. For the depth a component is buried, the room module is entirely accessible, however the wall component has other interfaces (the joints to the floor, ceiling, and other walls), that are less accessible. It may be easier therefore to change the function of a room module for technical and depth reasons, but harder to change the wall module since the wall to floor interface is connected and hidden.

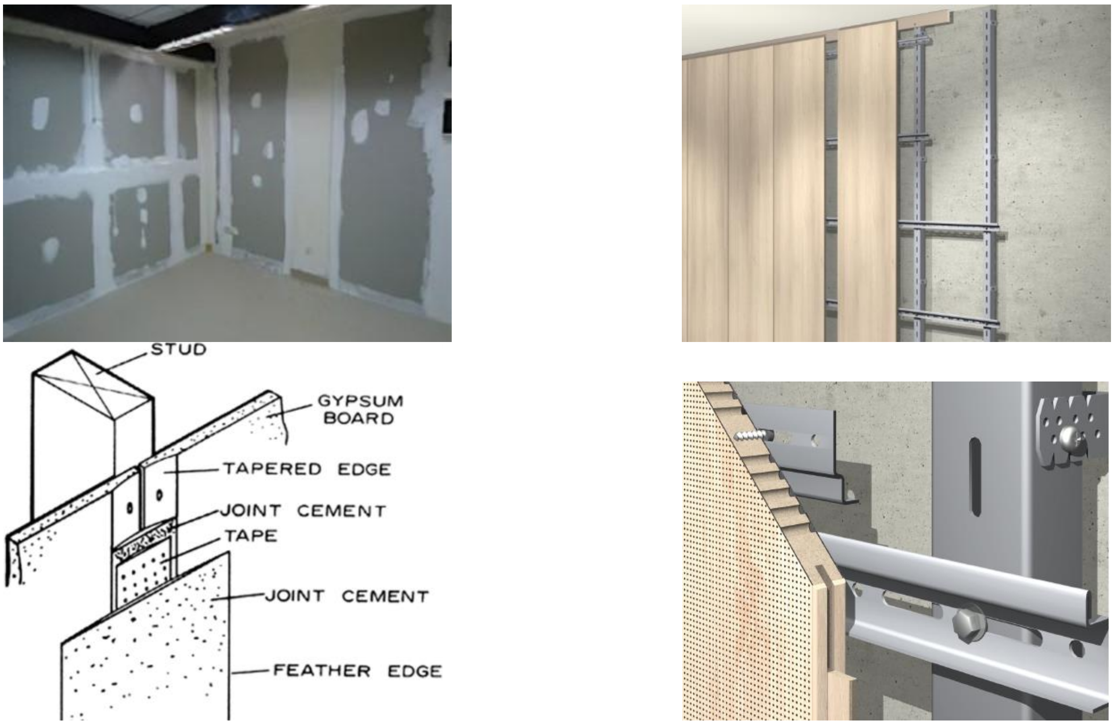

Figure 6: Left: Low-level reversibility wood framed gypsum board (Adapted from Civilguidelines.com images), and Right: high-level reversibility prefabricated panelized wall finish (Adapted from Ambienta Architectural Systems images)

STANDARDIZATION

The third characteristic Fixson describes, standardization, relates to the interface's role regarding substitutes. Considered to be critical for product variety, interface standardization measures the interfaces' role to facilitate module substitutes (components and spatial voids) and, in this case, building module component product families (room/spatial void types, wall modules, floor modules, ceiling modules, for example). Room types, like student accommodation rooms, or hotel rooms are highly repeatable, while a railway control center room is often a one off. For sub-components making up a module, the junction between a wall lining and the supporting wall is often a standard system (regardless of the degree of reversibility) as represented in both examples in Figure 6, versus a one-off rammed earth wall.

Standardization describes the degree to which an interface facilitates the swapping of components on either side of the interface. While standardization could be easily confused with Reversibility, a building example distinction for a component would be the difference between a nail and a screw. Both could be standard, but a nail does not facilitate reversibility, while a screw facilitates reversibility. Fixson clarifies that 'component swapping modularity and component sharing modularity do not describe the interface itself, but rather the alternatives that exist on either side of the interface.' The distinction being that component swapping, is usually where the larger component remains in the system, like a room, and the interface allows the exchange of the other one, like a wall. In our example of a room and wall, the larger component is exchanged by changing the function of the room from Bedroom to Living Room, hence it would be considered component sharing (the wall is shared), provided the wall component interface (the plane separating the two components – wall and room) with the room can accommodate the change of function. As a plane, this might seem straightforward for the interface between the two. However, the interface must be capable of exchanging all critical functions. Using the wall as the example, if the wall was acoustically rated for 40 dB (Decibels), and the Living Room requires separation to another Bedroom of 60 dB, the interface (plane) has failed to transfer the functional performance requirement since the wall component has only managed to address 40 dB of the interface requirement. The result being that the interface requirements must be maintained, and therefore the wall component module needs to be changed with another wall module type that meets those requirements.

Since interface planes in a building are similarly common across component types within a family, room to walls, for example, the interface systems are considered to have bus modularity. If the interface planes become standardized to the point they facilitate connection of every component with every other component, they would be considered sectional modularity. Looking at the types of interfaces at various similar module levels, rooms (spatial voids) to walls (components), for example, is where Fixson’s Lego standardization example is fitting.

CONCLUSION

This study has taken a view from product architecture that a building could be a combination of both component-oriented and space-oriented modules. A building module could be a component (door, wall, window, floor) and it could be a spatial void (room) to make the appropriate scale of these module interfaces invariant. Further, spatial voids are formed by at least six ‘planes’ (e.g. boundaries without psychical mass between two spatial voids) instead of ‘surfaces’ (e.g. associated with a solid mass such as a wall). A building module plane is the interface for both spatial and component modules, regardless of having a surface or not. This view gives greater flexibility in the definition of a building module to allow for multiple interfaces with other modules that are not dependent or linked to a surface.

By applying product modularity definitions to building modularity, testing interfaces through a different lens to what other literature has used, and applying them to Fixson’s tool, this study suggests the tool can be adapted and applied for use in building product architecture to define component module requirements. Following Ulrich's (1995) product architecture definition, after the function of the spatial void (room) is determined (and arranged in a floor plan), the functions can be mapped to the adjacent physical components (walls, ceiling floor, for example), through the interface plane connecting those components. Where interface planes (having interface characteristics, but no physical mass or thickness) are defined between spatial (rooms) and component (walls, floors, ceilings) oriented modules, with functions allocated to them from those modules, a clearer, more succinct set of component modules for manufacture and assembly can be defined.

IMPLICATIONS

The implications being that interface parameters assigned by the functional allocation from the spatial voids can be applied to an invariant interface database parametric management tool to be used for module component identification, selection, and meet functional spatial performance criteria. If used by designers initially, this tool, once developed, should provide building owners and maintainers greater certainty that the building designed will perform as intended, and can be maintained and changed easily while limiting disruption to occupants.

To inform an interface database functional allocation tool, more analytical research needs to be conducted into the design life of various components in various building types that make up assemblies, along with identifying the various change frequencies. This research will help inform the level in an assembly a modular or integral component might need to be. Additional research also needs to be conducted into the levels of disruption tolerable to building occupants in the various building usage types to help organize the modules.

The next step would be to define building module function categories (performance standards) from room requirements. These would be mapped to the interface characteristics (type, reversibility, and standardization) for transfer from a spatial module (rooms) across an interface plane to a component module (walls, floors, ceilings) and vice versa.

REFERENCES

Askar, R., Bragança, L., & Gervásio, H. (2021). Adaptability of Buildings: A Critical Review on the Concept Evolution. Applied Sciences, 11(10), 4483. https://doi.org/10.3390/app11104483

Ching, F. (2023). Architecture: Form, space, and order. John Wiley & Sons.

Eppinger, S. D., & Ulrich, K. (1995). Product design and development.

Fixson, S. K. (2005). Product architecture assessment: A tool to link product, process, and supply chain design decisions. Journal of Operations Management, 23(3–4), 345–369. https://doi.org/10.1016/j.jom.2004.08.006

Gershenson, J. K., Prasad, G. J., & Zhang, Y. (2003). Product modularity: Definitions and benefits. Journal of Engineering Design, 14(3), 295–313. https://doi.org/10.1080/0954482031000091068

Gleeson, C., Yang, J., & Lloyd-Jones, T. (2011). European Retrofit Network: Retrofitting Evaluation Methodology Report. University of Westminster.

Gosling, J., Sassi, P., Naim, M., & Lark, R. (2013). Adaptable buildings: A systems approach. Sustainable Cities and Society, 7, 44–51. https://doi.org/10.1016/j.scs.2012.11.002

Grussing, M. N., & Liu, L. Y. (2014). Knowledge-Based Optimization of Building Maintenance, Repair, and Renovation Activities to Improve Facility Life Cycle Investments. Journal of Performance of Constructed Facilities, 28(3), 539–548. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000449

Keymer, M. A. (2000). Design Strategies for New and Renovation Construction that Increase the Capacity of Buildings to Accommodate Change.

Knyziak, P., Krentowski, J. R., & Bieranowski, P. (2017). Risks of the Durability of Large-Panel Buildings Elevations in Reference to the Conclusions from Technical Conditions Audits. MATEC Web of Conferences, 117, 00080. https://doi.org/10.1051/matecconf/201711700080

Menassa, C. C., & Baer, B. (2014). A framework to assess the role of stakeholders in sustainable building retrofit decisions. Sustainable Cities and Society, 10, 207–221. https://doi.org/10.1016/j.scs.2013.09.002

Pimmler, T. U., & Eppinger, S. D. (1994). Integration Analysis of Product Decompositions. 6th International Conference on Design Theory and Methodology, 343–351. https://doi.org/10.1115/DETC1994-0034

Pine, B. J. (1999). Mass customization: The new frontier in business competition. Harvard business press.

Rocha, C., Formoso, C., & Tzortzopoulos, P. (2015). Adopting Product Modularity in House Building to Support Mass Customisation. Sustainability, 7(5), 4919–4937. https://doi.org/10.3390/su7054919

Rocha, C. G. da, Tezel, A., Talebi3, S., & Koskela, L. (2018). Product Modularity, Tolerance Management, and Visual Management: Potential Synergies. 582–592. https://doi.org/10.24928/2018/0482

Salvador, F., Forza, C., & Rungtusanatham, M. (2002). How to mass customize: Product architectures, sourcing configurations. Business Horizons, 45(4), 61–69. https://doi.org/10.1016/S0007-6813(02)00228-8

Sanchez, R. (1995). Strategic flexibility in product competition. Strategic Management Journal, 16(S1), 135–159.

Schilling, M. A. (2000). Toward a general modular systems theory and its application to interfirm product modularity. Academy of Management Review, 25(2), 312–334.

Slaughter, E. S. (2001). Design strategies to increase building flexibility. Building Research & Information, 29(3), 208–217. https://doi.org/10.1080/09613210010027693

Tokede, O., & Ahiaga-Dagbui, D. (2016). Evaluating the Whole-Life Cost Implicaiton of Revocability and Disruption in Office Retrofit Building Projects. 10.

Ulrich, K. (1994). Fundamentals of Product Modularity. In S. Dasu & C. Eastman (Eds.), Management of Design (pp. 219–231). Springer Netherlands. https://doi.org/10.1007/978-94-011-1390-8_12

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. Research Policy, 24(3), 419–440. https://doi.org/10.1016/0048-7333(94)00775-3

Vickery, S. K., Bolumole, Y. A., Castel, M. J., & Calantone, R. J. (2015). The effects of product modularity on launch speed. *International Journal of Production Research*, *53*(17), 5369–5381. https://doi.org/10.1080/00207543.2015.1047972